Experiment Based Teaching of Solar Cell Operation and Characterization Using the SolarLab Platform

Spataru, Sergiu; Sera, Dezso; Kerekes, Tamas; Teodorescu, Remus; Cotfas, Petru Adrian; Cotfas, Daniel Tudor

Published in:
Proceedings of the 7th International Workshop on Teaching in Photovoltaics

Publication date:
2014

Document Version
Early version, also known as pre-print

Experiment Based Teaching of Solar Cell Operation and Characterization Using the SolarLab Platform

S. V. Spataru, D. Sera, T. Kerekes, R. Teodorescu
Department of Energy Technology
Aalborg University, Aalborg, Denmark

P. A. Cotfas, D. T. Cotfas
Electronics and Computers Dept.
Transilvania University of Brasov, Romania

Abstract

Experiment based teaching methods are a great way to get students involved and interested in almost any topic. This paper presents such a hands-on approach for teaching solar cell operation principles along with characterization and modelling methods. This is achieved with the SolarLab platform which is a laboratory teaching tool developed at Transylvania University of Brasov. Using this platform, solar cells can be characterized under various illumination, temperature and angle of light incidence. Additionally, the SolarLab platform includes guided exercises and intuitive graphical user interfaces for exploring different solar cell principles and topics.

The exercises presented in the current paper have been adapted from the original exercises developed for the SolarLab platform and are currently included in the Photovoltaic Power Systems courses (MSc and PhD level) taught at the Department of Energy Technology, Aalborg University.

Keywords: characterization, experiment based, modelling, solar cell, teaching photovoltaics

INTRODUCTION

Teaching solar cell operation theory can be greatly enhanced by complementing it with experiments and hands-on exercises, where the students get to characterize solar cells under various operation conditions, apply the theory they have learned, and compare the theoretical and experimental results obtained.

Such an approach has been adopted successfully at Aalborg University for teaching solar cell operation and characterization methods, based on the SolarLab platform.

Several exercises have been devised based on this laboratory platform, for experimental characterization of crystalline silicon and thin film solar cells under variable illumination conditions, temperature, angle of light incidence, and analysing the measured I-V characteristic and solar cell efficiency in conjunction with the theory.

Other exercises have been formulated in order to illustrate solar cell modelling techniques such as: identifying the single diode model parameters from I-V measurements, or different methods for estimating series and shunt resistance.

Such a hands-on approach is possible since the SolarLab platform offers an intuitive and easy to use hardware and graphical user interface, making it ideal for teaching purposes.

These exercises are currently being used successfully in the Photovoltaic Power Systems courses (MSc and PhD level) taught at the Department of Energy Technology, Aalborg University.

SOLAR CELL MODELLING

The theoretical operation of most solar cells can be described by the single diode model (1), presented in detail in [1], where: I is the output current of the solar cell; V - terminal voltage; I_{ph} - photo-generated current; I_o - diode reverse saturation current; R_s – lumped series resistance of the cell; R_{sh} - lumped shunt resistance of the cell; V_t – thermal voltage.

$$I = I_{ph} - I_o\left[\exp\left(\frac{V+IR_s}{V_t}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \quad (1)$$

The photo-generated current I_{ph} is dependent on the effective irradiance reaching the solar cell (E), as well as on the cell temperature (T_c) and can be approximated using (2), where $I_{ph,ref}$ represents the photo-generated current measured at $T_{c,ref}$ and E_{ref}, whilst α_{Isc} is the a empirical thermal coefficient [1].

$$I_{ph} = \frac{E}{E_{ref}}\left[I_{ph,ref} + \alpha_{Isc}\left(T_c - T_{c,ref}\right)\right] \quad (2)$$

The thermal voltage (Vt) and diode saturation current (I_o) are temperature dependent parameters, described by the relationships (3) and (4), where n is the diode ideality factor; q - electron charge; k - Boltzmann's constant; E_g is the material band gap [1].

$$V_t = \frac{nkT_c}{q} \quad (3)$$

$$I_o = I_{o,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left[\frac{1}{k}\left(\frac{E_g}{T_c} - \frac{E_{g,ref}}{T_{c,ref}}\right)\right] \quad (4)$$

The model in (1) along with the irradiance and temperature dependent equations in (2), (3) and (4) can describe the solar cell operation and I-V characteristic curve over a range of operating conditions if parameterized adequately. The model parameters are most often calculated from datasheet values [2, 3] or measurements [4], after which the I-V curve of the solar cell can be numerically simulated from (1).

Three operation points on the I-V curve are of special interest for understanding solar cell operation and for designing photovoltaic systems: the short-circuit point ($I=I_{sc}$, $V=0$); the open circuit point ($I=0$, $V=V_{oc}$) and the maximum power point ($I=I_{mp}$, $V=V_{mp}$).

At the short circuit operation point ($I=I_{sc}$,$V=0$) the solar cell model (1) can be rewritten as in (5), which allows to approximate the photo-generating capabilities (I_{ph}) of the solar cell with the short-circuit current (I_{sc}) under certain conditions (6). This approximation is limited by the potential losses that can occur in the solar cell, as is the case of solar cells with high series resistance (R_s>10 cm^2) [5], or significant shunting.

$$I_{sc} = I_{ph} - I_o\left[\exp\left(\frac{I_{sc}R_s}{V_t}\right) - 1\right] - \frac{I_{sc}R_s}{R_{sh}} \quad (5)$$

$$I_{sc} \cong I_{ph}, \text{for } R_s \ll R_{sh} \text{ and } I_o \ll I_{ph} \quad (6)$$

The solar cell operation can be described at the open circuit ($I=0$, $V=V_{oc}$) as in (7), and assuming a high shunt resistance (R_{sh}), the solar cell open circuit voltage (V_{oc}) can be approximated as in (8). From here we can infer the main factors influencing the voltage of the solar cell are: the temperature through the thermal voltage (V_t), followed to a lesser extent by the irradiance (through I_{ph}).

$$0 = I_{ph} - I_o\left[\exp\left(\frac{V_{oc}}{V_t}\right) - 1\right] - \frac{V_{oc}}{R_{sh}} \quad (7)$$

$$V_{oc} = V_t \ln\left(\frac{I_{ph}}{I_o} + 1\right) \text{ for } R_{sh} \gg V_{oc} \quad (8)$$

The maximum power point (*MPP*) is maybe the most important parameter relating to PV system performance and operation. Analytically be derived from the solar cell model using (9) resulting in highly nonlinear equations. Practically the MPP is estimated using maximum power tracking algorithms.

$$\left.\frac{dP}{dV}\right|_{\substack{I=I_{mp}\\ V=V_{mp}}} = 0 \quad (9)$$

SOLARLAB PLATFORM

The SolarLab platform has been developed by Cotfas et al at Transilvania University of Brasov, Romania as a hands-on tool for teaching photovoltaic (PV) cell operation and characterization principles to undergraduate and graduate students. The teaching platform consists of a hardware system for performing experiments and measurements on solar cells, a control software and graphical user interface implemented in LabView, as well as a manual [6] for performing guided exercises and experiments with the platform.

Hardware System

The hardware system is based on the NI Educational Laboratory Virtual Instrumentation Suite (NI ELVIS) design and prototyping platform, which has been expanded as in Fig. 1a, for performing measurements on solar cells at various illumination levels, temperature and angles of light incidence. For this purpose, a custom board has been developed, as shown in Fig. 1, below:

Fig. 1 Top view of the SolarLab platform: a) NI ELVIS II development board; b) custom SolarLab control and measurement board; c) stepper motor control; d)I-V characterization; e)temperature control; f)light control; g) halogen lamp; h) stepper motor; i)solar cell support including heater and sensors.

Graphical User Interface

The measurement and control software has been implemented in LabView, on top of which the several experiments and exercises have been developed, each with its own customized graphical user interface (GUI). An example GUI for experimental study of the solar cell operation under variable illumination levels is presented in Fig. 2. In version 1.0 of the SolarLab platform 15 exercises have been implemented so far, some of which have been adapted for the PVPS course at Aalborg University and are summarized in the current paper.

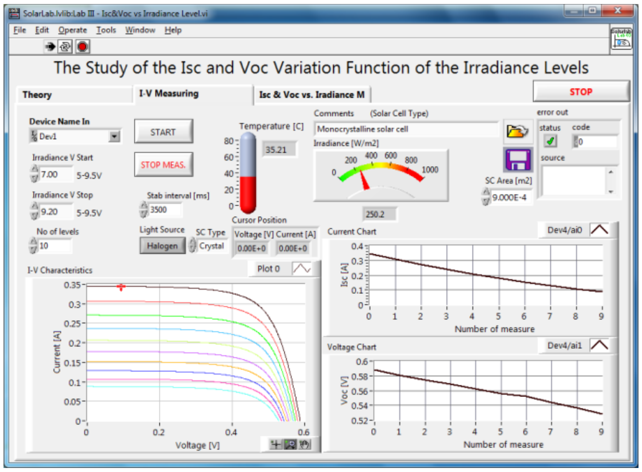
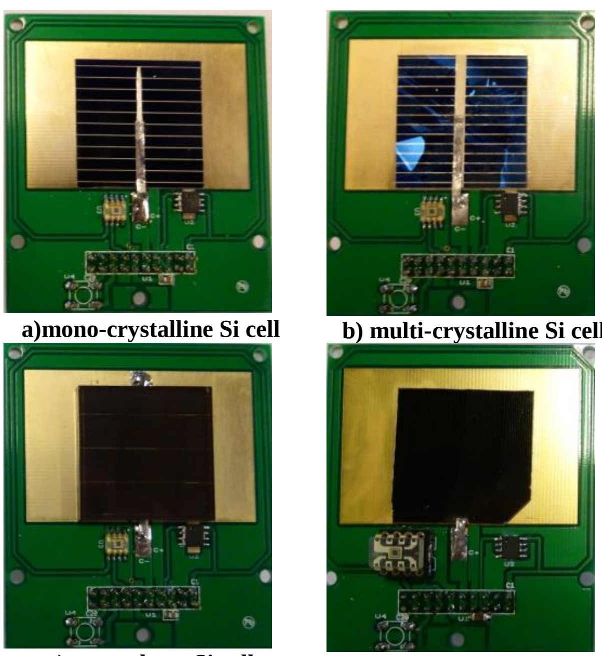


Fig. 2 Graphical User Interface in LabView for one of the exercises.

Experiment Materials

For the purpose of studying the difference between solar cell technologies, four types (c-Si, mc-Si, a-Si and GaAs) of solar cells samples have been developed so far for the SolarLab platform. The special solar cell samples presented in Fig. 3 each include additional to the solar cell, a plane of array illumination sensor, a heater and temperature sensor, which all connect to the main control board.



a)mono-crystalline Si cell **b) multi-crystalline Si cell**

c) amorphous Si cell **d)GaAs cell**

Fig. 3 Top view of the four cell types used with the SolarLab platform, together with their measurement circuits. All units include cell temperature control.

SOLAR CELL OPERATION AND CHARACTERIZATION EXERCISES

The following exercises have the purpose to demonstrate and teach solar cell operation principles and modelling methods for crystalline and thin film solar cells. This is achieved by experimental study of the solar cell I-V characteristic curve under variable illumination, temperature and angle of light incidence, as well as correlation of the experimental result with the theoretical solar cell model and equations.

Variable Illumination Conditions

This exercise will investigate the effect of variable illumination on the solar cell I-V characteristic curve and performance parameters, for solar cells of different technologies (c-Si, mc-Si, a-Si and GaAs). The experiment will be performed on the SolarLab platform, which is able to measure and control the illumination level (200 to 1000 W/m^2) shined upon the solar cell sample.

Laboratory task 1. Perform the following tasks:

a) Measure the I-V characteristic curves of each solar cell sample at variable illumination levels (between 200 and 1000 W/m^2), and observe the effect of irradiance changes on the I-V characteristic for each of the solar cell types, as in Fig. 4 and Fig. 5.
b) Calculate the variation of I_{sc} and V_{oc} with irradiance, relative to the 1000 W/m^2 measured values, for all four solar cell samples, and plot these values as in Fig. 6.

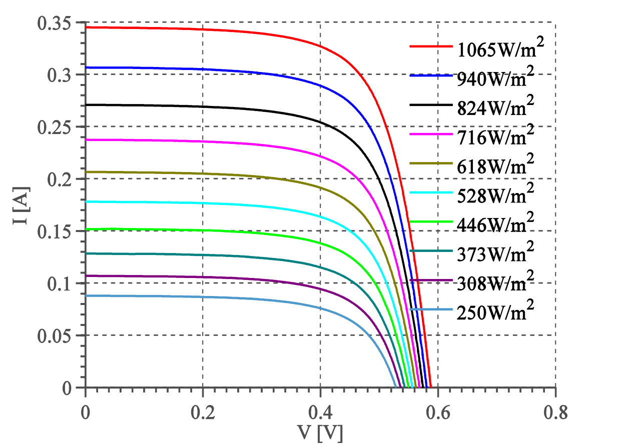


Fig. 4 Variable illumination effect on the I-V characteristic of a c-Si solar cell, measured with the SolarLab platform.

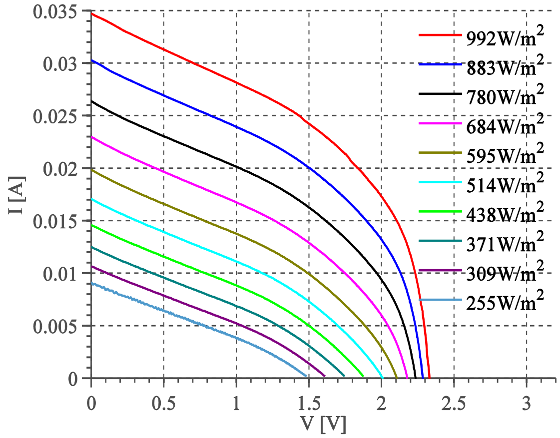


Fig. 5 Variable illumination effect on the I-V characteristic of a GaAs solar cell, measured with the SolarLab platform.

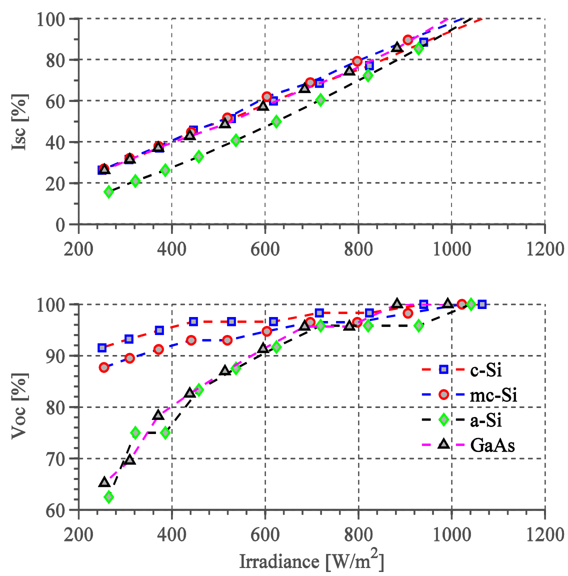


Fig. 6 Relative (to 1000 W/m²) change of the short circuit current (I_{sc}) and open circuit voltage (V_{oc}) to variable irradiance.

Questions for task 1. Answer the following questions:

a) What kind of dependency is there between the short circuit current and the irradiance levels? How does it correlate with the assumptions and equations in (2), (5) and (6)?

b) What about the dependency between the open circuit voltage and the irradiation levels? How does it correlate with the assumptions and equations in (7) and (8).

Laboratory task 2. Perform the following tasks:

a) Calculate the variation of maximum power P_{max}, corresponding current I_{mp} and voltage V_{mp}, relative to the 1000 W/m² measured values, for all four solar cell samples, and plot these values as in Fig. 7.

b) Calculate the cell efficiency η and fill factor FF for each solar cell at the variable illumination levels, using (10) and (11), and plot them as in Fig. 8.

$$\eta = \frac{P_{\max}}{S \times Area} \times 100 \tag{10}$$

$$FF = \frac{P_{\max}}{V_{oc} \times I_{sc}} \tag{11}$$

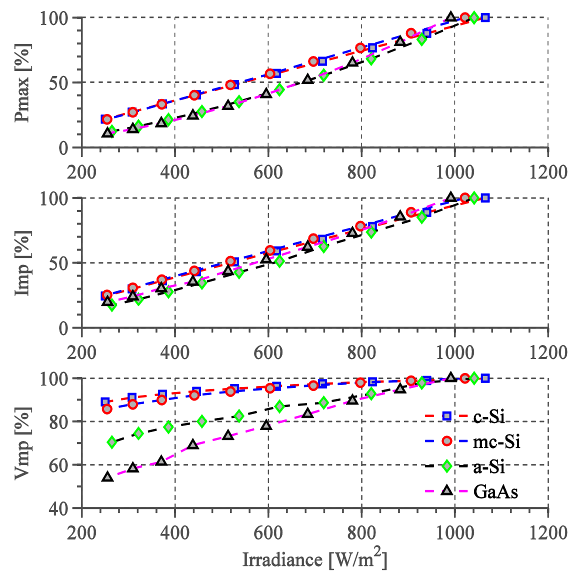


Fig. 7 Relative (to 1000 W/m²) change of the maximum power (P_{max}), corresponding current (I_{mp}) and voltage (V_{mp}) to variable irradiance.

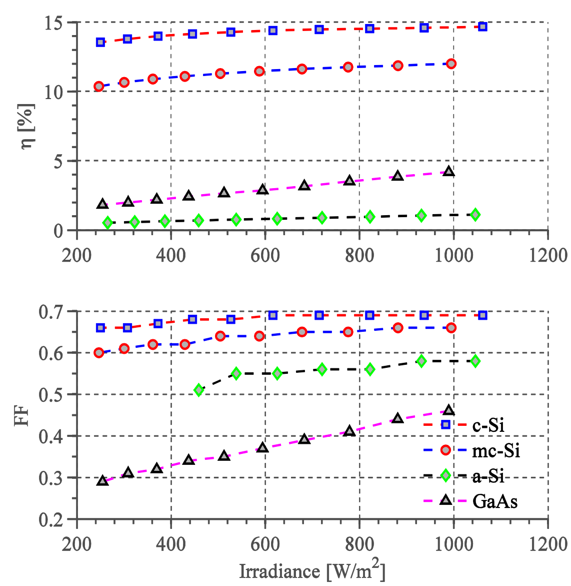


Fig. 8 Relative (to 1000 W/m²) change of the solar cell efficiency (η) and fill factor (*FF*) to variable irradiance.

Questions for task 2. Answer the following questions:

a) Comment on the dependence of P_{max}, I_{mp} and V_{mp} on irradiance conditions? How does the variation of P_{max},

I_{mp} and V_{mp} with irradiance influence PV system design and inverter sizing?

b) What is the difference in solar cell efficiency between the crystalline and thin film solar cells?

Variable Temperature Conditions

The next exercise will investigate the temperature dependence of the solar cell I-V characteristic curve and performance parameters, for solar cells of different technologies (c-Si, mc-Si, a-Si and GaAs). The experiment will be performed on the SolarLab platform which is able to control the temperature of the solar cell sample in increments of 5 ºC from room temperature to 65 ºC using a feedback loop control of the cell temperature.

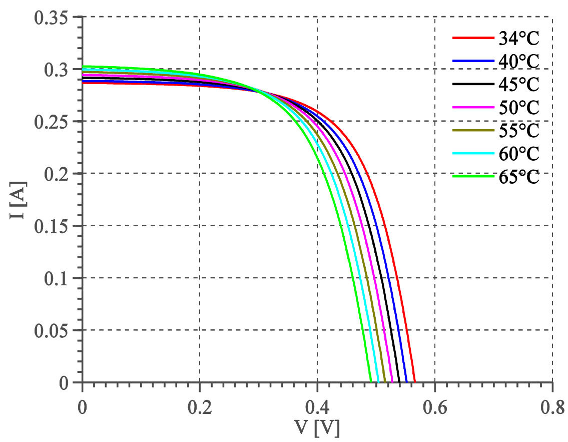


Fig. 9 Variable cell temperature effect on the I-V characteristic of a mc-Si solar cell, measured with the SolarLab platform.

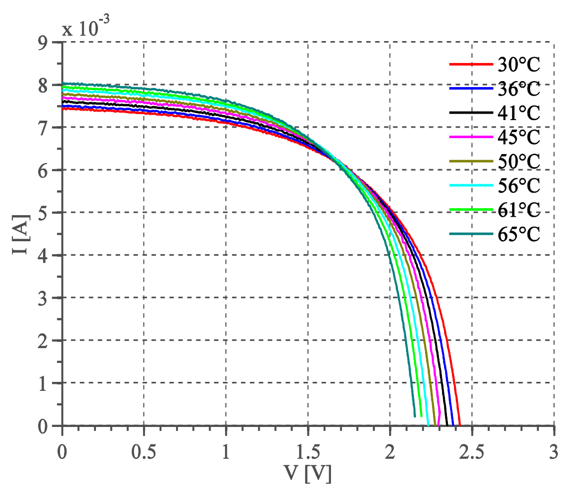


Fig. 10 Variable cell temperature effect on the I-V characteristic of an a-Si solar cell, measured with the SolarLab platform.

Laboratory task 3. Perform the following tasks:

a) Measure the I-V characteristic curves of each solar cell sample at different temperature levels (between room temperature and 65 ºC), and observe the effect of increasing temperature on the I-V characteristic for the different solar cell types, as in Fig. 9 and Fig. 10.

b) Calculate the variation of I_{sc} and V_{oc} with temperature, relative to the room temperature measured values, for all four solar cell samples, and plot these values as in Fig. 11.

Questions for task 3. Answer the following questions:

a) What kind of dependency is there between the short circuit current and the temperature? How about open circuit voltage and temperature?

b) What parameter is most affected by the increase in temperature?

Laboratory task 4. Perform the following tasks:

a) Calculate the variation of maximum power P_{max}, corresponding current I_{mp} and voltage V_{mp}, relative to the room temperature measured values, for all four solar cell samples, and plot these values as in Fig. 12.

b) Calculate the temperature coefficients for I_{sc}, V_{oc}, I_{mp}, V_{mp}, P_{max} using (12) and compare them between the four solar cell technologies as in Table 1.

$$T.C. = \frac{1}{p}\frac{\delta p}{\delta T}\bigg|_{T_{ref}=25^{\circ}C} \cong \frac{p - p_{ref}}{p_{ref}\left(T - T_{ref}\right)} \qquad (12)$$

c) Calculate the cell efficiency η and fill factor FF for each solar cell at the variable illumination levels, using (10) and (11), and plot them as in Fig. 13.

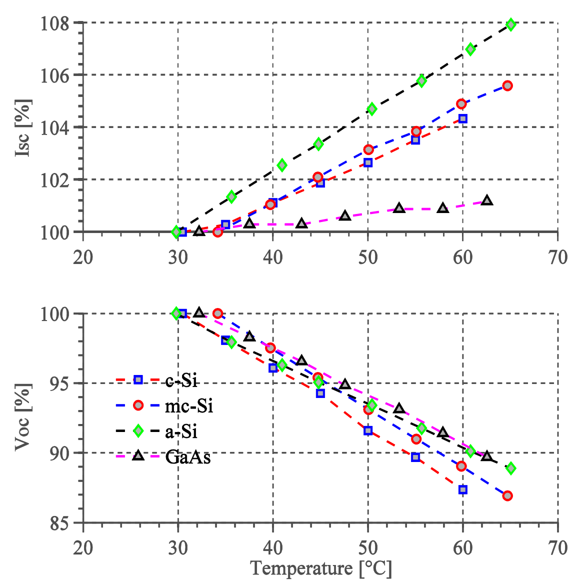


Fig. 11 Relative (to room temperature ~30ºC) change of the short circuit current (I_{sc}) and open circuit voltage (V_{oc}) to variable temperature.

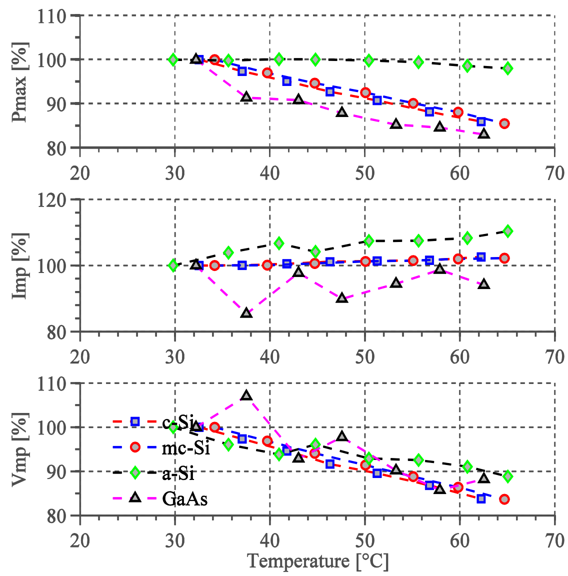


Fig. 12 Relative (to room temperature ~30ºC) change of the maximum power (P_{max}), corresponding current (I_{mp}) and voltage (V_{mp}) to variable temperature.

Table 1 Temperature coefficients calculated for I_{sc}, V_{oc}, I_{mp}, V_{mp} and P_{max} of each solar cell.

T.C. [%/K]	c-Si	mc-Si	a-Si	GaAs
α-I_{sc}	0.1516	0.1845	0.2244	0.0371
β-V_{oc}	-0.4269	-0.4263	-0.3128	-0.3382
α-I_{mp}	0.0844	0.0788	0.2398	0.0411
β-V_{mp}	-0.5405	-0.5299	-0.2636	-0.5709
γ-P_{max}	-0.4636	-0.4546	-0.0482	-0.5903

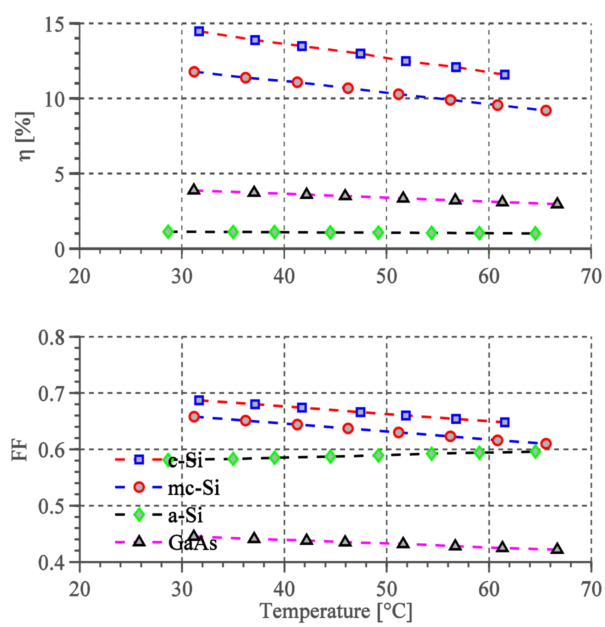


Fig. 13 Relative (to room temperature) change of the solar cell efficiency (η) and fill factor (*FF*) to variable temperature.

Questions for task 4. Answer the following questions:

a) Comment on the dependence of P_{max}, I_{mp} and V_{mp} on increasing temperature?

b) What is the difference in solar cell efficiency between the crystalline and thin film solar cells? Which would be more suitable for a hot climate? What about a cold climate?

Variable Angle of Light Incidence

The last exercise in this section will investigate the influence of the angle of light incidence on the effective irradiance reaching the solar cell (characterized by I_{sc}) and on the other solar cell performance parameters. Four types of solar cells are investigated (c-Si, mc-Si, a-Si, GaAs), having different light absorption and reflection properties. The experiment will be performed on the SolarLab platform which is able to control the tilt angle of the solar cell (in relation to the light source) from 0º to 85º, in increments of 5º.

Laboratory task 5. Perform the following tasks:

a) Measure the I-V characteristic curves of each solar cell sample at variable inclination angles of the solar cell (between 0 and 85º), and observe the effect of the angle of light incidence has on the I-V characteristic for the four solar cell types.

b) Calculate the variation of I_{sc}, V_{oc} and P_{max} with the angle of light incidence, relative to the 0º measured values, for all four solar cell samples, and plot these values as in Fig. 14.

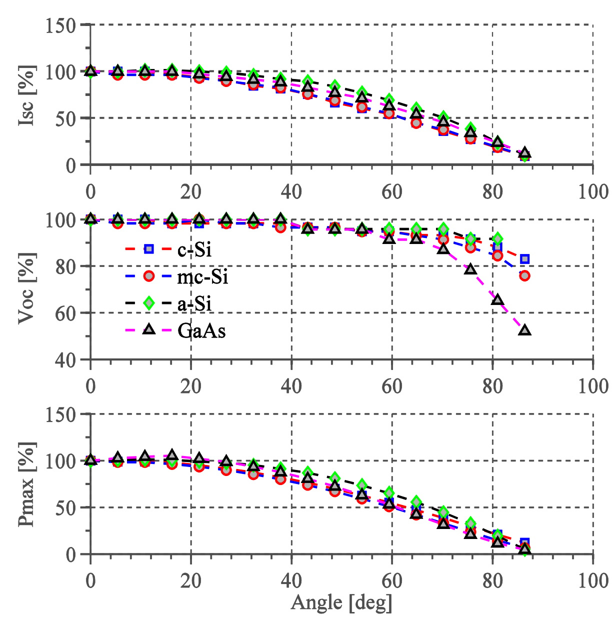


Fig. 14 Relative (to 0º) change of the short circuit current (I_{sc}), open circuit voltage (V_{oc}) and maximum power (P_{max}) to variable angle of light incidence.

Questions for task 5. Answer the following questions:

a) What kind of dependence is there between I_{sc} and the angle of light incidence? What about V_{oc} and P_{max}?
b) Explain why there is a difference in the angle of light incidence dependence between solar cells.

MODEL PARAMETER IDENTIFICATION EXERCISES

The following exercises have the purpose to teach different methods for determining the solar cell model parameters, along with their advantages and limitations. The methods are demonstrated experimentally for the four types of solar cells presented previously, using the SolarLab platform.

Determination of the Model Parameters by Nonlinear Curve Fitting

The most general method for calculating the diode model parameters for a solar cell is to curve fit the measured light I-V characteristic curve of the solar cell to the model in (1). Non-linear fitting methods such as Levenberg–Marquardt or other non-linear least squares algorithms can yield very accurate curve fits, if the model parameter search space is expanded sufficiently, and initial conditions are chosen judiciously. The consequence of expanding the parameter search space to get a good curve fits can be the result in model parameters with values void of any correlation with physical processes occurring in the solar cell (such as negative resistance, of ideality factors with large values).

Some partial solutions to this problem can be: to limit the parameter search space, which would lead to less accurate curve fitting; to use a more detailed solar cell model, such as the double diode model [7]; or to implement a more detailed parameter identification method which makes use of more solar measurements and/or the expert knowledge of the user [4].

Table 2 Single diode model parameters calculated from non-linear curve fitting of the light I-V curve measured at 1000 W/m^2 and ~27ºC

	c-Si	mc-Si	a-Si	GaAs
Rs [Ω]	**0.0317**	**0.0128**	**0**	**0**
Rsh [Ω]	**50.36**	**68.968**	**2136.2**	**149.64**
I0 [A]	**2.45E-6**	**2.8E-5**	**2.366E-6**	**1.66E-7**
n	**1.917**	**2.4**	**11.63**	**7.74**
Iph [A]	**3.29E-1**	**2.83E-1**	**7.57E-3**	**3.47E-2**

Laboratory task 6. Perform the following tasks:

a) Measure the I-V curve at 1000 W/m^2 and room temperature for each solar cell.
b) Calculate the model parameters (R_s, R_{sh}, n, I_{ph}, I_o) by curve fitting the measured I-V curves to the solar cell model in (1).
c) Compare the resulting model parameters for each solar cell technology as in Table 2.

Questions for task 6. Answer the following questions:

a) Compare the I_{sc} and I_{ph} of each solar cell. Does the approximation in (6) hold?
b) How to you explain the difference in model parameters between the crystalline and the thin film solar cells?
c) Is the single diode model suitable for the thin film solar cells used in the experiment? What about the crystalline cells?

Determination the Model Parameters from Analytical Equations

Many alternatives to curve fitting the diode model parameters have been presented in the literature having various degrees of complexity and applicability. Some methods [3] are based on simplifying assumptions about the model which work well for certain types of solar cells for which those assumptions hold, having the advantage of being easy to implement. Other methods [2, 8, 9] are based on mixed numerical and analytical method, with an increased complexity and applicability to wider ranges of solar cell types.

Regardless of the method employed in identifying the model parameters, the accuracy and physical correlation of those parameters will be limited by the model itself, and its capability to capture the main physical processes occurring in the solar cell.

Table 3 Single diode model parameters calculated using the analytical method from [2] and the light I-V curve measured at 1000 W/m^2 and ~27ºC

	c-Si	mc-Si	a-Si	GaAs
Rs [Ω]	**0.214**	**0.279**	**29.4**	**6.43**
Rsh [Ω]	**269.07**	**147.85**	**3970**	**138.86**
I0 [A]	**2.95E-6**	**1.25E-5**	**6.72E-7**	**3.24E-14**
n	**1.88**	**2.21**	**10.2**	**3.32**
Iph [A]	**3.34E-1**	**2.83E-1**	**7.33E-3**	**3.65E-2**

Laboratory task 7. Perform the following tasks:

a) Measure the I-V curve at 1000 W/m^2 and room temperature for each solar cell.
b) Calculate the model parameters (R_s, R_{sh}, n, I_{ph}, I_o) from the measured I-V curves by using the analytical equations presented in [2].
c) Compare the resulting model parameters for each solar cell technology as in Table 3.

Questions for task 7. Answer the following questions:

a) Compare the diode model parameters resulted from the analytical method (Table 3) with those from the non-linear curve fitting (Table 2).
b) How to you explain the difference in the series resistance calculated using the two methods? What about the shunt resistance?

Determination of the Series and Shunt Resistances from the IV Curve derivative

Identifying and analysing the diode model parameters is an invaluable tool in understanding the characteristics of a solar cell and evaluating its operation and performance in various locations and ambient conditions, not readily available through measurements.

Additional to identifying all the diode model parameters, there are methods for estimating only specific parameters which are of special interest in detection potential losses and faults occurring in the PV device. Two of these parameters are the series and shunt resistance, which are lumped parameters correlated with the series and shunt current losses occurring in a solar cell.

The absolute value of these parameters is a good indicator in quantifying solar cell quality and monitoring the manufacturing process [10]. Relative changes in these parameters (increases in series resistance, or decreases of the shunt resistance) can indicate faults and degradation affecting the solar cell such as corrosion [11], water ingress [11], cell interconnect break [12], degradation of the junction box terminations [13], or cell shunting [13].

Various methods for calculating series and shunt resistance have been proposed in the literature [14] involving various degrees of complexity and types of measurements required. A simple method for estimating the series and shunt resistance is based on calculating the slope of the I-V characteristic at I_{sc} and V_{oc} respectively as in (13) and (14). This method does not yield exact values for the resistances but can give an indication of the rough values [13] and on the relative resistance changes occurring in the solar cell, which is of great use in PV system diagnostics.

$$R_{s0} = -\left.\frac{dV}{dI}\right|_{I=0} \tag{13}$$

$$R_{sh0} = -\left.\frac{dV}{dI}\right|_{I=I_{sc}} \tag{14}$$

Laboratory task 8. Perform the following tasks:

a) Measure the I-V curve at 1000 W/m^2 and room temperature for each solar cell.
b) Calculate the series resistance R_{s0} and the shunt resistance R_{sh0} from the slope of the I-V characteristic near V_{oc} and I_{sc} respectively.
c) Compare the resulting resistance parameters for each solar cell technology as in Table 4.

Table 4 Series and shunt resistance calculated from the I-V curve

	c-Si	mc-Si	a-Si	GaAs
Rs0 [Ω]	**0.231**	**0.270**	**31.79**	**5.6**
Rsh0 [Ω]	**711.4**	**216.05**	**3874.4**	**119.5**

Questions for task 8. Answer the following questions:

a) Compare the resistance values obtained in Table 4 with those obtained through curve fitting the diode model (Table 2) and from the analytical model equations (Table 3).
b) How well does the estimated series resistance in Table 4 match the curve fitted values in Table 2? What about the shunt resistance?

Determination of the Series Resistance Using the Two IV Characteristic method

A simple yet accurate method for calculating the series resistance of a PV device, first presented in detail in [5], is based on measuring two I-V characteristic curves at different light intensities and constant temperature. By choosing two operation points (V_1, I_1) and (V_2, I_2) near the V_{mp} of each I-V curve such that the relation (15) is satisfied, the series resistance can be calculated as in (16).

$$I_2 = I_1 - \Delta I_{sc} \tag{15}$$

$$R_s = \frac{V_1 - V_2}{I_{sc1} - I_{sc2}} = \frac{\Delta V}{\Delta I_{sc}} \tag{16}$$

Several improvements and derivations of the method have been developed over the years, such as combining low light with high irradiance IV measurements [15], dark I-V with light I-V measurements [16], or combining multiple light I-V curves to calculate the series resistance, as is the case of the latest edition of the IEC 60891 standard [17].

Laboratory task 9. Perform the following tasks:

a) Measure two I-V curve at 400 W/m^2, 1000 W/m^2 and room temperature for each solar cell.
b) Calculate the series resistance R_s according to the procedure described in [5] and using (15) and (16)
c) Compare the resulting series resistance parameters for each solar cell technology as in Table 5.

Table 5 Series calculated from two I-V curves

	c-Si	mc-Si	a-Si	GaAs
Rs [Ω]	**0.142**	**0.146**	**25**	**3.3**

Questions for task 9. Answer the following questions:

a) Compare the series resistance values obtained in Table 5 with those obtained through the previous methods Table 2, Table 3 and Table 4.
b) Chose other V_1 and V_2 points farther away from the V_{mpp}, are recalculate the series resistance. How does the new calculation point change the estimation series resistance and why?

SUMMARY AND DISCUSSION

The SolarLab platform is a flexible and easy to use teaching tool permitting students to get hands on experience and interest in photovoltaics. The solar cell operation theory and principles can be complemented by experiments and exercises performed by the students. Topics such as solar cell operation and efficiency under variable illumination, temperature and angle of light incidence can be easily approached and demonstrated in the laboratory for crystalline and thin film PV technologies, without the need of expensive solar simulators. Several solar cell characterization and modelling methods have been already developed as exercises on the SolarLab platform, and these can be further expanded with other methods and exercises of interest.

REFERENCES

[1] W. De Soto, S. A. Klein, and W. A. Beckman, “Improvement and validation of a model for photovoltaic array performance,” *Solar Energy,* vol. 80, no. 1, pp. 78-88, 1//, 2006.

[2] D. S. H. Chan, J. R. Phillips, and J. C. H. Phang, “A comparative study of extraction methods for solar cell model parameters,” *Solid-State Electronics,* vol. 29, no. 3, pp. 329-337, 3//, 1986.

[3] D. Sera, R. Teodorescu, and P. Rodriguez, "PV panel model based on datasheet values." pp. 2392-2396.

[4] C. Hansen, "Estimation of Parameters for Single Diode Models Using Measured IV Curves."

[5] M. Wolf, and H. Rauschenbach, “Series resistance effects on solar cell measurements,” *Advanced Energy Conversion,* vol. 3, no. 2, pp. 455-479, 4//, 1963.

[6] D. Cotfas, and P. Cotfas, *Solarlab Manual - Experiments in Photovoltaic Cells*, Brasov, Romania, 2011.

[7] K. Ishaque, Z. Salam, and H. Taheri, “Simple, fast and accurate two-diode model for photovoltaic modules,” *Solar Energy Materials and Solar Cells,* vol. 95, no. 2, pp. 586-594, 2//, 2011.

[8] A. P. Dobos, “An Improved Coefficient Calculator for the California Energy Commission 6 Parameter Photovoltaic Module Model,” *Journal of Solar Energy Engineering,* vol. 134, no. 2, pp. 021011-021011, 2012.

[9] D. T. Cotfas, P. A. Cotfas, and S. Kaplanis, “Methods to determine the dc parameters of solar cells: A critical review,” *Renewable and Sustainable Energy Reviews,* vol. 28, no. 0, pp. 588-596, 12//, 2013.

[10] D. L. King, B. R. Hansen, J. A. Kratochvil, and M. A. Quintana, "Dark current-voltage measurements on photovoltaic modules as a diagnostic or manufacturing tool." pp. 1125-1128.

[11] E. L. Meyer, and E. E. van Dyk, “Assessing the reliability and degradation of photovoltaic module performance parameters,” *IEEE Transactions on Reliability,* vol. 53, no. 1, pp. 83-92, Mar, 2004.

[12] G. Kunz, and A. Wagner, "Internal series resistance determinated of only one IV-curve under illumination."

[13] E. Van Dyk, and E. Meyer, “Analysis of the effect of parasitic resistances on the performance of photovoltaic modules,” *Renewable energy,* vol. 29, no. 3, pp. 333-344, 2004.

[14] M. Bashahu, and A. Habyarimana, “Review and test of methods for determination of the solar cell series resistance,” *Renewable Energy,* vol. 6, no. 2, pp. 129-138, 3//, 1995.

[15] S. Bowden, and A. Rohatgi, "Rapid and Accurate Determination of Series Resistance and Fill Factor Losses in Industrial Silicon Solar Cells."

[16] P. Hacke, and D. L. Meier, “Analysis of fill factor losses using current-voltage curves obtained under dark and illuminated conditions,” *Conference Record of the Twenty-Ninth Ieee Photovoltaic Specialists Conference 2002*, pp. 462-464, 2002.

[17] IEC, "IEC 60891:2009 - Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics," International Electrotechnical Commission, 2009.

Addresses of the authors:

Sergiu Spataru, Pontoppidanstraede 101, 9220 Aalborg, DK, ssp@et.aau.dk
Dezso Sera, Pontoppidanstraede 101, 9220 Aalborg, DK, des@et.aau.dk
Tamas Kerekes, Pontoppidanstraede 101, 9220 Aalborg, DK, tak@et.aau.dk
Remus Teodorescu, Pontoppidanstraede 101, 9220 Aalborg, DK, ret@et.aau.dk
Petru Adrian Cotfas, Eroilor 29, 500036 Brasov, Ro, pcotfas@unitbv.ro
Daniel Tudor Cotfas, Eroilor 29, 500036 Brasov, Ro, dtcotfas@unitbv.ro